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Analysis of Field Design Considerations for the Operation of Undersea Sensor Networks

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Presented at 2008 MORS Symposium
10-12 June 2008

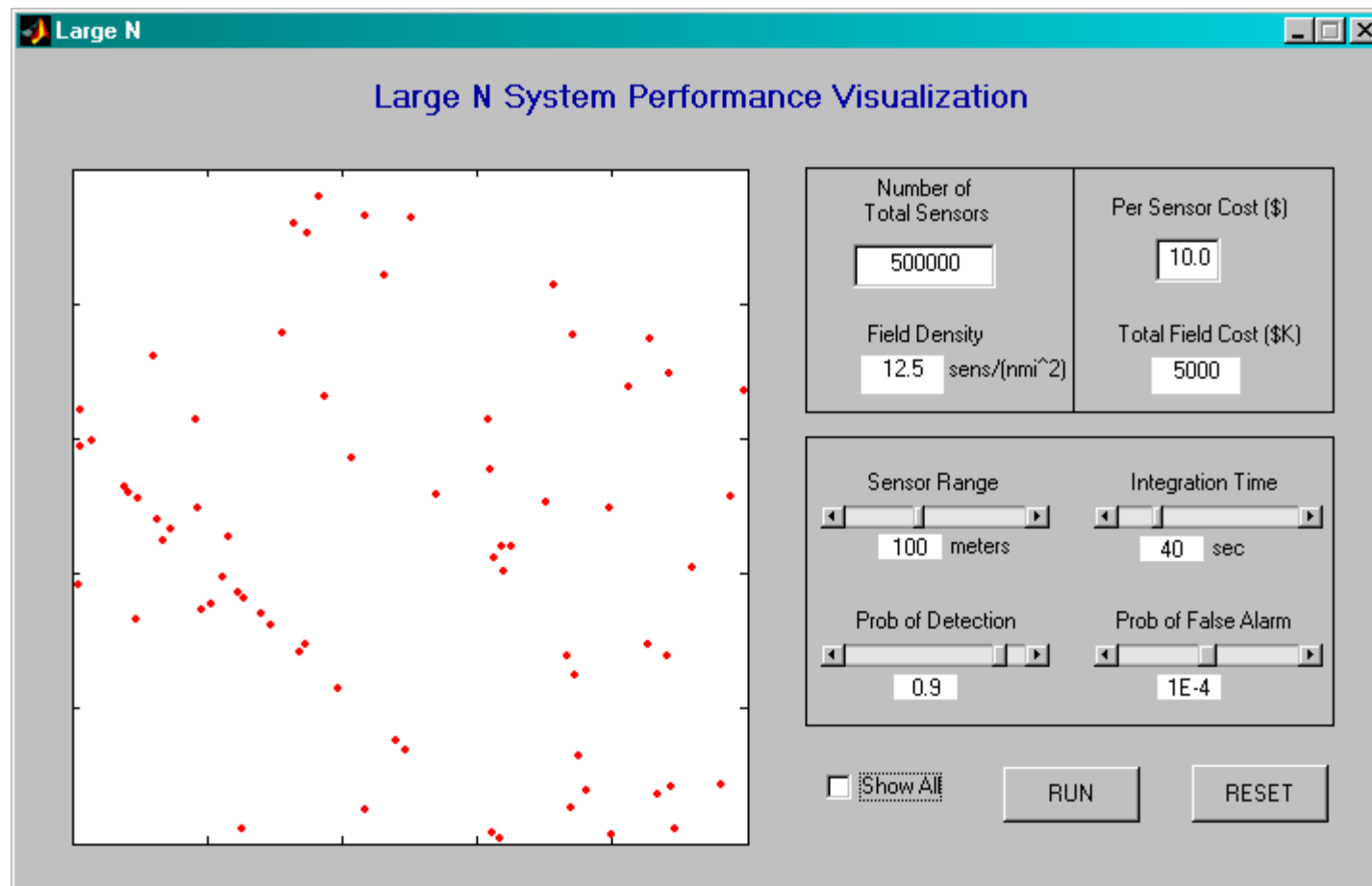
What is the Navy Problem?

- ASW (Anti-submarine warfare) is a critical challenge for maintaining a Fleet presence in hostile areas
- ONR (code 321MS) has been supporting our research to develop the mathematical tools to address the problem of optimal design, employment, and control of distributed ASW sensors in complex and variable environments.
- In the undersea environment, there are some unique challenges:
 - Very large areas (order of 10^4 nmi²) must be covered covertly
 - Prosecuting false alerts is very expensive and dangerous
 - Sensors move (drift) in an undesirable manner
 - Environmental uncertainty affects the decision-making process
 - Target variability affects decision-making (high false alerts)
 - Communications under water is limited to acoustics (low data rate and high power) and pop-up RF (repeatability?)

Want to use as few as possible, as cheap as possible, as quickly as possible, with high probability of detection and low false alarms.

Isn't this Easy?

- How simple/complex can distributed tracking be?
- If we visually examine detections, will target location be obvious?





A Distributed Sensing Problem



Problem: Determine the proper “sizing” of sensor fields to obtain tradeoffs between multi-sensor detection and multi-sensor false alarm performance as a function of the anticipated target characteristics.

Approach: Build analytical parametric models of system performance as a function of:

- (uncertain) target characteristics,
- (uncertain) sensor characteristics
- (uncertain) environmental characteristics

Then exercise the models to examine the effects of various deployment considerations on both detection and false alarm performance of the resulting field.

Consider the effects of environment and placement of sensors by examining the functions numerically compared to effective sensor density.

Consider parameters such as “time for multiple detections” as variables to be set by examination of the tradeoffs.

Probability of Successful Search Model

Let P_d be the probability of a **sensor detecting** the target when the target is within range R_d .

Define $f(\mathbf{x})$ as the positional sensor density distribution

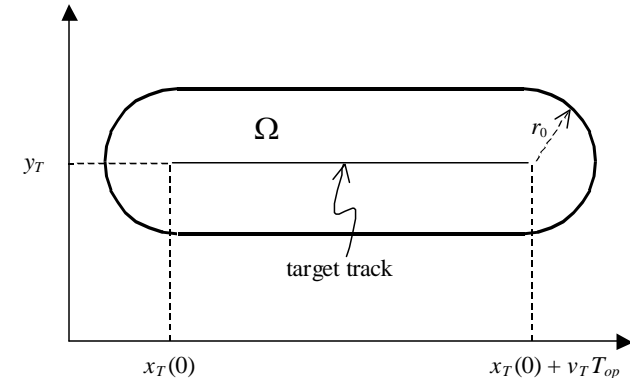
Then the effective fractional area coverage around a single sensor, given by the region Ω , is given by

$$\phi = \int_{\Omega} f(\mathbf{x}) d\mathbf{x}$$

The sensor is within range if it falls within the region Ω around the target track.

Thus, the probability of an individual sensor detection during T is given by :

$$p = P_d \phi \quad (\text{or } p = 1 - \exp(-P_d \phi) \text{ for "random search"})$$



**Sensor
Detects**

For N such sensors in a **field**, the probability of a successful **search** requiring "at least" k detections is :

$$P_{SS}(\geq k \text{ detections}) = 1 - \sum_{m=0}^{k-1} \binom{N}{m} p^m (1-p)^{N-m} \approx 1 - \exp(-Np) \sum_{m=0}^{k-1} \frac{(Np)^m}{m!}$$

For the case of uniformly distributed sensors, we have $f(\mathbf{x}) \rightarrow 1/A_0$, such that

$$\phi \rightarrow \frac{A_{\Omega}}{A_0} = \frac{2R_d VT + \pi R_d^2}{A_0}$$

**Field
Searches**

Probability of False Search Model

A sequence of false alarms, in a certain spatial/kinematic sequence, may trigger a false search result in the track-before-detect scheme

Assume a sensor density given by $f(\mathbf{x})$, note that for uniform $f(\mathbf{x}) \rightarrow 1/A_0$

The probability of a false track occurring around a specific pill region Ω , located at \mathbf{x}_0 , is given by

$$P_{FT}(\Omega(\mathbf{x}_0); k) = 1 - \exp(-NP_{fa} A_{\Omega} f(\mathbf{x}_0)) \sum_{m=0}^{k-1} \frac{(-NP_{fa} A_{\Omega} f(\mathbf{x}_0))^m}{m!}$$

For a search region S of area A_0 , the probability of one of these events(false track)occurring anywhere is given by

$$P_{FS}(k) = 1 - \exp\left(-\pi \int_S \frac{P_{FT}(\Omega(\mathbf{x}); k)}{A_{\Omega}} d\mathbf{x}\right)$$

Which we call the "probability of false search".

Under an approximation of small ϕ (recall that $\phi = A_{\Omega}/A_0$), we get

$$P_{FS}(k) \approx 1 - \left(\frac{1}{A_0} \int_S \exp(-NP_{fa} A_{\Omega} f(\mathbf{x})) \sum_{m=0}^{k-1} \frac{(-NP_{fa} A_{\Omega} f(\mathbf{x}))^m}{m!} d\mathbf{x} \right)^{\pi/\phi}$$

Both the P_{SS} and P_{FS} models have been validated via comparison with MUSICAL Monte Carlo simulations.

Reduced Equations for Analysis

- Some parameter combinations to facilitate the analysis:

$$\text{Target Motion Search Rate} = \nu = \frac{2VR_d}{A_0}$$

$$\text{Fractional Coverage of Individual Sensor} = \xi = \frac{\pi R_d^2}{A_0}$$

$$\text{Target Motion Search Growth Factor} = \eta = \frac{VT}{R_d}$$

- Leading to:

$$\text{Probability of Successful Search (for nominal search region)} =$$

$$= P_{SS}(NP_d\phi) = 1 - \exp(-NP_d\phi) \sum \frac{(NP_d\phi)^m}{m!}$$

$$\phi = \xi \left(1 + \frac{2}{\pi} \eta\right) = \xi + \nu T$$

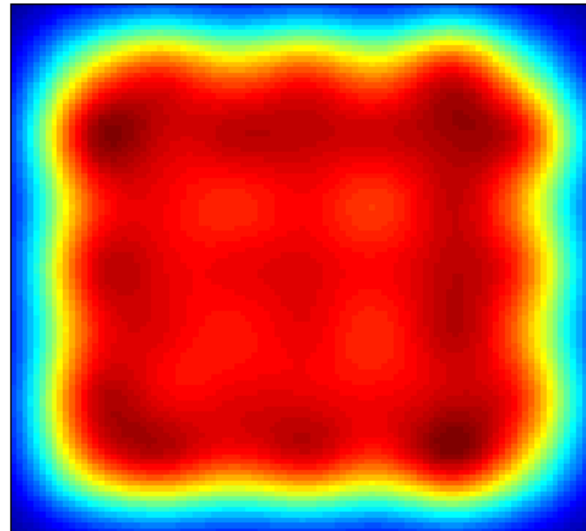
Values for Analysis

Case	Number of sensors N	Fractional coverage of individual sensor ξ	Target motion search rate ν	Number of required individual sensor detections
Many small sensors with slow targets	1000	0.005	0.1 hrs ⁻¹	2
Many small sensors with fast targets	1000	0.005	0.5 hrs ⁻¹	2
Few large sensors with slow targets	50	0.01	0.1 hrs ⁻¹	2
Few large sensors with fast targets	50	0.01	0.5 hrs ⁻¹	2

Note : $P_{ss} (2 \text{ detections}) = 1 - \exp(-N\phi)[1 + N\phi]$

with $\phi = \xi + \nu T$

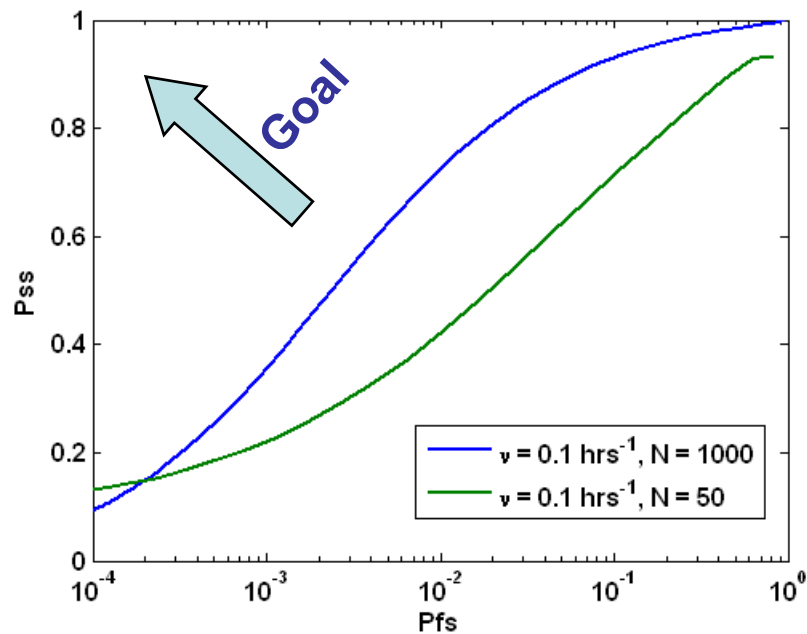
Goal Distribution



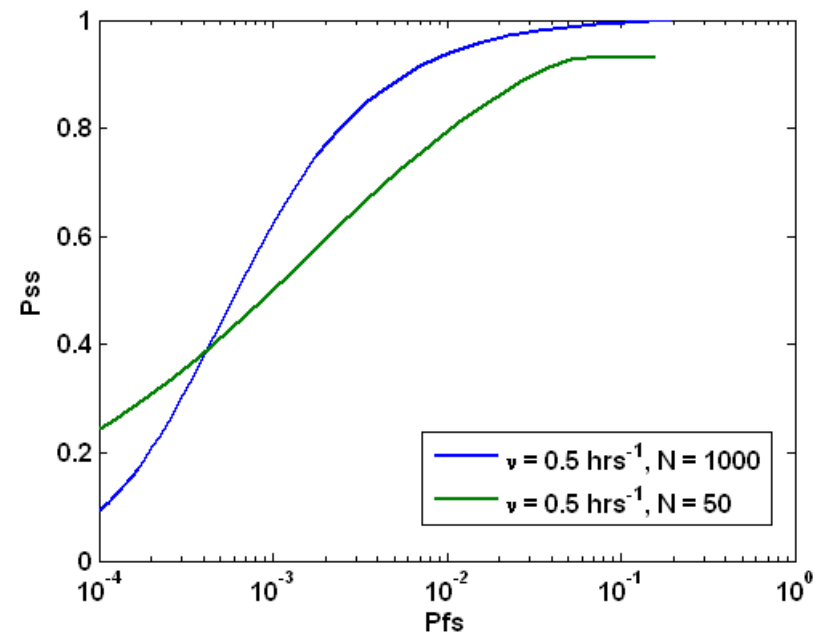
Goal is to place sensors within search region but not on edges.

P_{SS} vs P_{FS} Tradeoff for Goal Distribution

Slower Targets



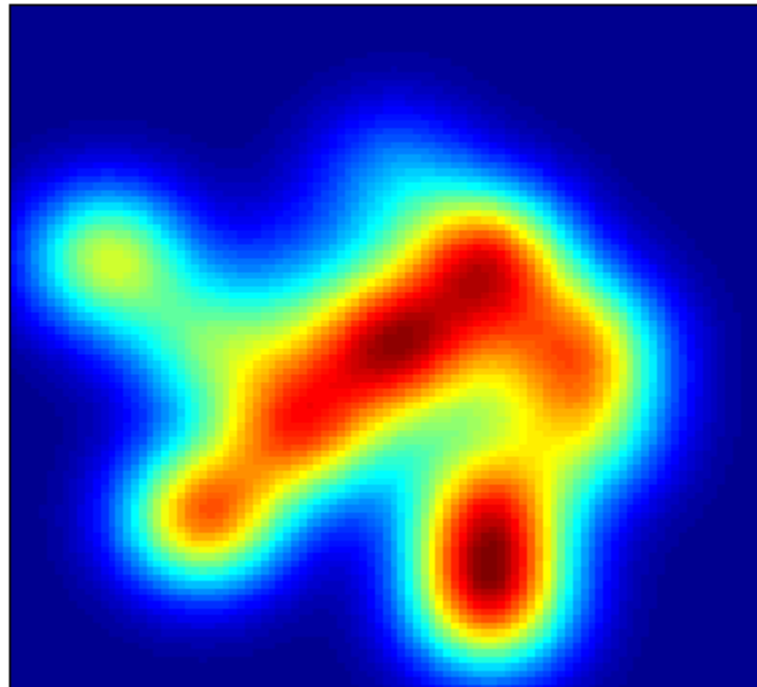
Faster Targets



Note: Variable running along curves is time to get multiple detections (T)

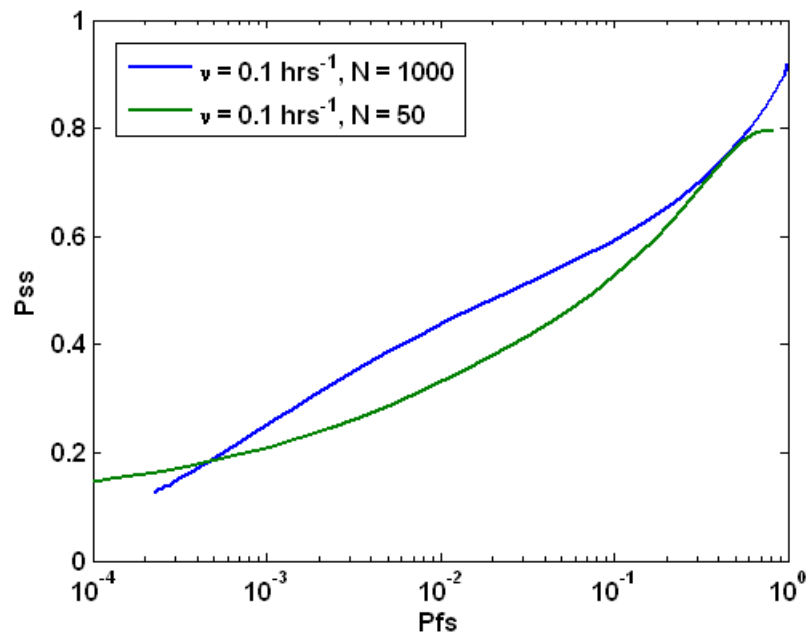
Clumped Distribution

In a real deployment, the distribution becomes more clumped, either directly due to sensor motion/drift/deployment, or due to a change in effective sensor density due to environmental performance.

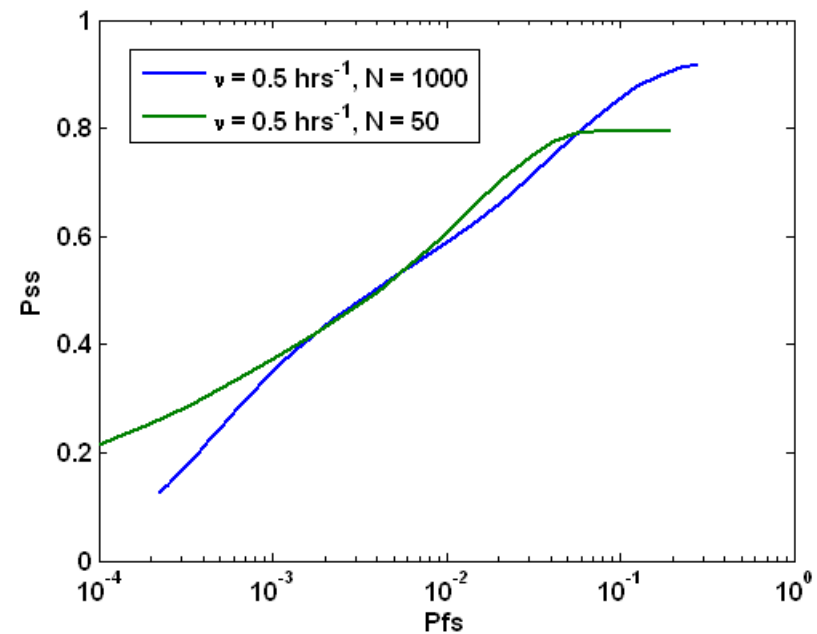


P_{SS} vs P_{FS} Tradeoff for Clumped Distribution

Slower Targets



Faster Targets



Note: Variable running along curves is time to get multiple detections (T)

Conclusions

- For sensors that are uniformly distributed:
 - For small time between detections, smaller numbers of larger sensors provide a better tradeoff
 - For long time between detections, larger numbers of smaller sensors provide a better tradeoff
 - These conclusions are consistent independent of expected target speed
- For sensors that have highly clumped distribution:
 - The tradeoffs are similar to the uniform case for slow expected target speeds
 - However, the smaller number of larger sensors dominates for fast expected target speeds, regardless of time between detections
- These methods and tools can be exercised in other parameter combinations to examine other issues in the deployment of distributed undersea sensors.